



Computational Fluid Dynamics Analysis of Ballast Water Sampling

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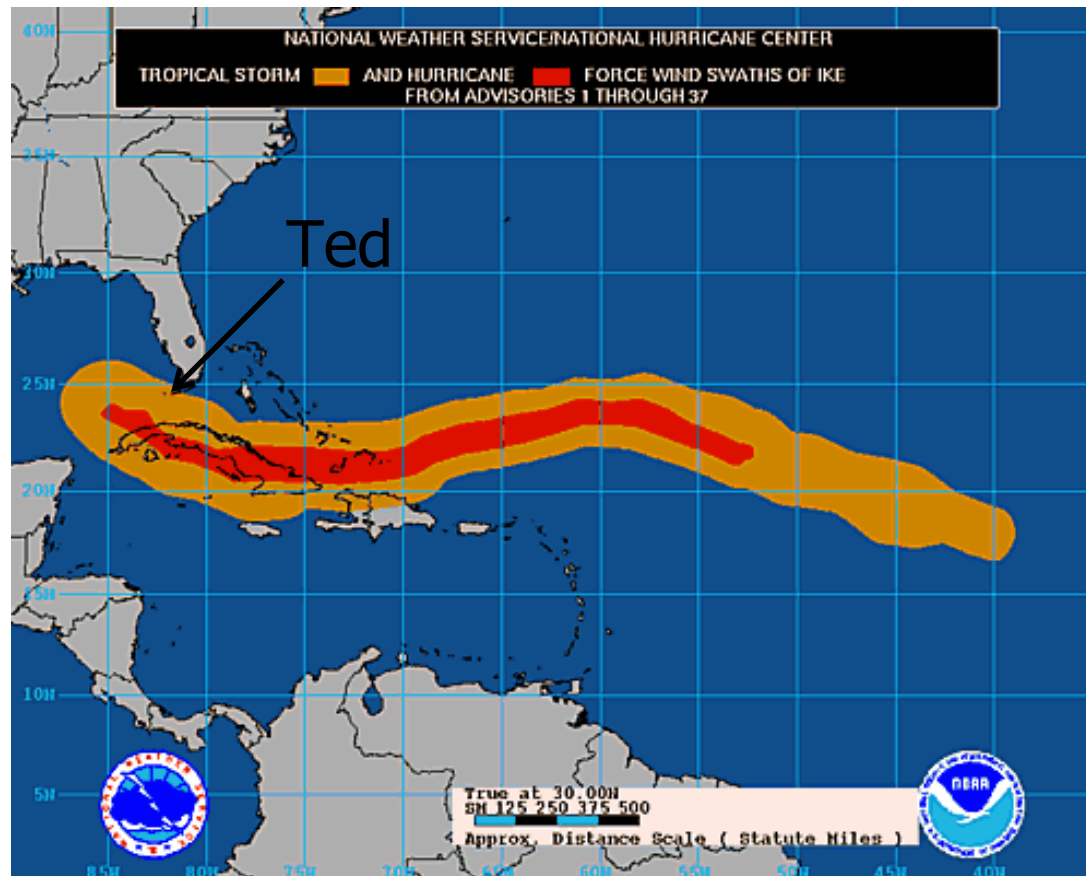
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Computational Fluid Dynamics of Ballast Water Sampling

Things Got Complicated for Ted





Background

- The US Coast Guard in coordination with the Naval Research Laboratory have an ongoing S&T effort to investigate and address technical challenges related to land based and shipboard testing of ballast water treatment systems.
- In FY06, we initiated a computational effort to examine the hydrodynamics of sampling pipe flows with entrained organisms or particles.



Objective

- Provide a computational examination of the sampling strategy in use at NRL for testing
- Examine the hydrodynamics related to various sample port designs
- Establish design and application guidelines for ballast water sampling design, location and installation which provide a representative sample of the actual discharge that minimizes adverse affects on sampled organisms.



Computational Analysis & Assumptions

- COSMOSFloWorks® was used for the CFD analysis
 - Numerical methods to solve the Navier Stokes Equations which describe fluid motion for Newtonian fluids.
 - Provide the velocity or flow field and allows for the calculation of particle trajectories.
 - Design for use with turbulent flows
- Since organisms are generally neutrally buoyant, they will mirror the velocity field unlike lubricants, oils, sediments and other immiscible second phase flows.
 - Organisms do not segregate
 - Organism distribution, velocity are modeled by the flow



BASIC FLOW CALCULATIONS

- Flow is generally characterized by the non-dimensional Reynolds Number:

$$Re = \frac{\rho v_s^2 / L}{\mu v_s / L^2} = \frac{\rho v_s L}{\mu} = \frac{v_s L}{\nu} = \frac{\text{Inertial forces}}{\text{Viscous forces}}$$

- v_s - mean fluid velocity, [m s⁻¹]
- L - characteristic length, [m]
- μ - (absolute) dynamic fluid viscosity, [N s m⁻²] or [Pa s]
- ν - kinematic fluid viscosity: $\nu = \mu / \rho$, [m² s⁻¹]
- ρ - fluid density, [kg m⁻³].
- For turbulent flows, fully developed flow is established at the non-dimensional entrance length (E_L):

$$E_L = 4.4 \cdot \frac{1}{\sqrt{Re}} = \frac{4.4}{\sqrt{Re}}$$

- l_e - the distance required to achieve fully developed flow
- D - is the pipe diameter



Computational Fluid Dynamics of Ballast Water Sampling

Flow Characteristics for NRLKW Piping & Sample Ports

Ballast Water Sampling NRL Test System Basic Flow Parameters

Main Piping:

8 inch Schd 40 PVC Pipe ID := 7.981 in OD := 8.625 in

$$A_p := \frac{\pi \cdot ID^2}{4}$$

$$A_p = 50 \text{ in}^2$$

Where A_p is the cross sectional area of the pipe

Assume Pipe to be Smooth

Main Piping Flow Characteristics:

Sea Water Density $\rho_{sw} := 64.02 \frac{\text{lb}}{\text{ft}^3}$ $\rho_{sw} = 1026 \frac{\text{kg}}{\text{m}^3}$

Dynamic Viscosity $\mu := 1.06 \text{ centipoise}$ $\mu = 1.06 \times 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}}$

Kinematic Viscosity $\nu := \frac{\mu}{\rho_{sw}}$ $\nu = 1.034 \times 10^{-6} \frac{\text{m}^2}{\text{s}}$

Nominal Flow Rate $Q_{sw} := 300 \frac{\text{m}^3}{\text{hr}}$ $Q_{sw} = 5085 \frac{\text{in}^3}{\text{sec}}$

Average Velocity $V_{sw} := \frac{Q_{sw}}{A_p}$ $V_{sw} = 101.7 \frac{\text{in}}{\text{sec}}$

Reynolds Number $R_{esw} := \frac{ID \cdot V_{sw}}{\nu}$ $R_{esw} = 5.1 \times 10^5$

Sample Piping

1 ½ in. Schd 40 PVC ID_s := 1.61 in OD_s := 1.90 in

$$A_s := \frac{\pi \cdot ID_s^2}{4}$$

$$A_s = 2 \text{ in}^2$$

Where A_s is the cross sectional area of the sample pipe

Nominal Flow Rate, Q

$$Q_s := 3 \frac{\text{m}^3}{\text{hr}}$$

$$Q_s = 51 \frac{\text{in}^3}{\text{sec}}$$

$$Q_s = 13.2 \frac{\text{gal}}{\text{min}}$$

Average Velocity, V

$$V_s := \frac{Q_s}{A_s}$$

$$V_s = 25 \frac{\text{in}}{\text{sec}}$$

Reynolds Number

$$R_{es} := \frac{ID_s \cdot V_s}{\nu}$$

$$R_{es} = 3 \times 10^4$$

Reynolds Number > 4000

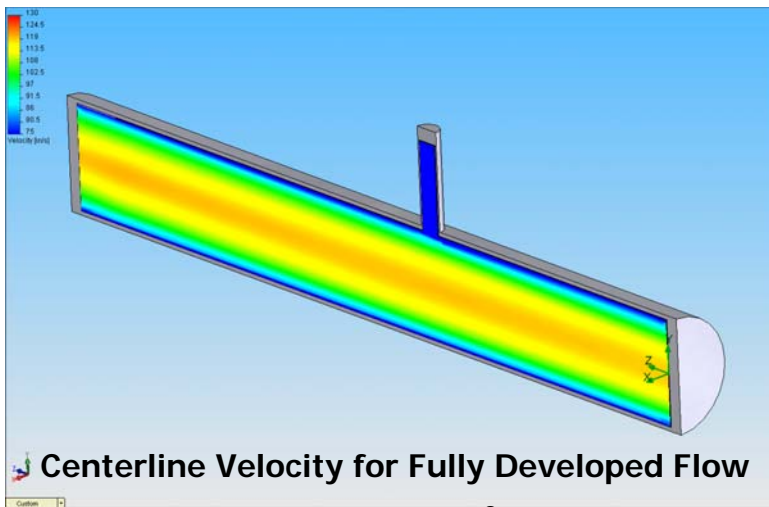
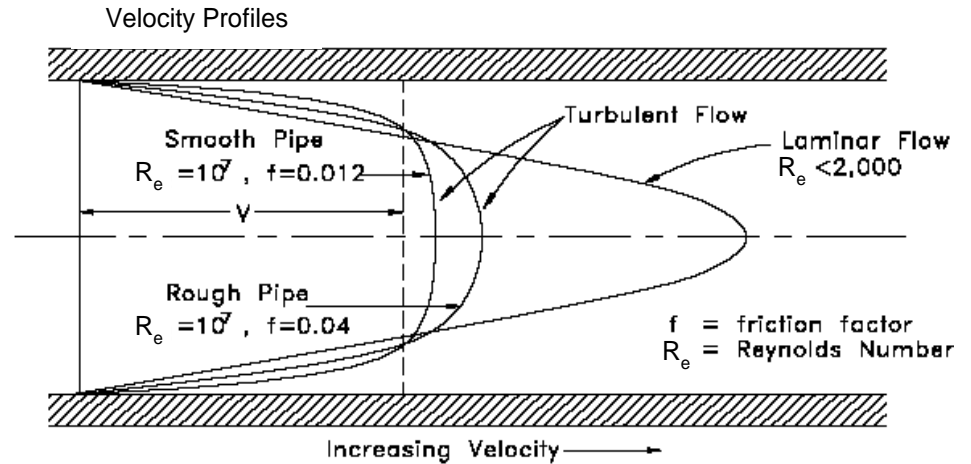
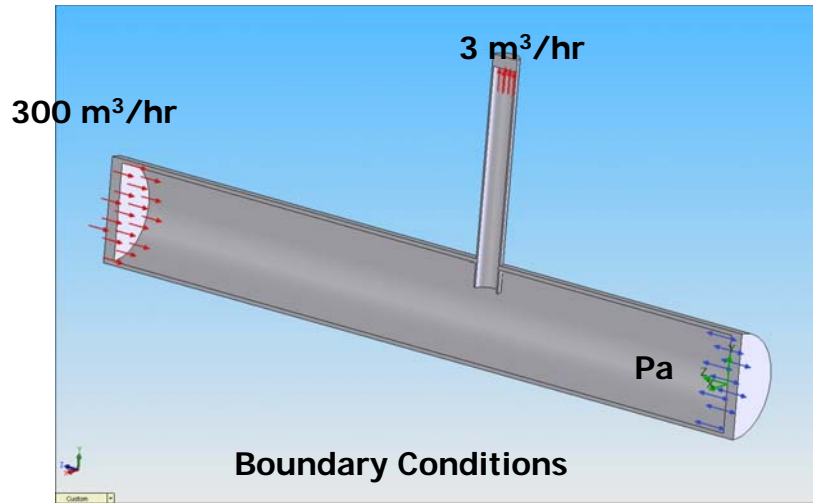
Flow is Fully Turbulent

Reynolds Number > 4000 Flow is Fully Turbulent

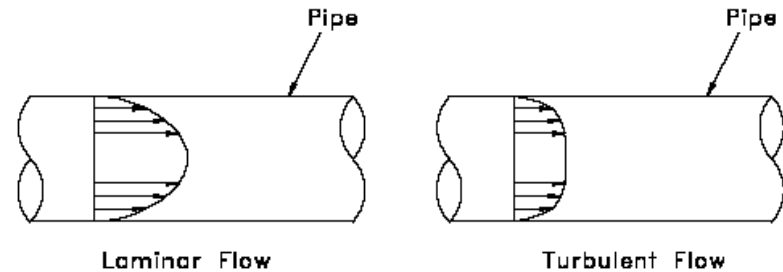


Computational Fluid Dynamics of Ballast Water Sampling

Boundary Conditions and Fully Developed Velocity Contours

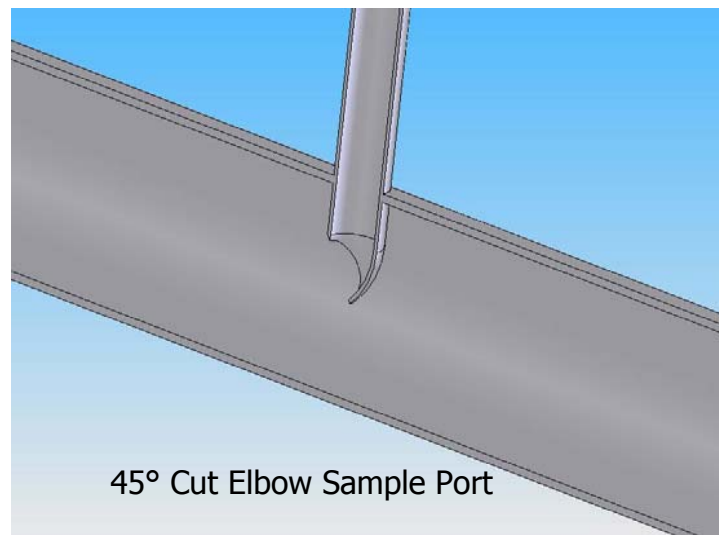
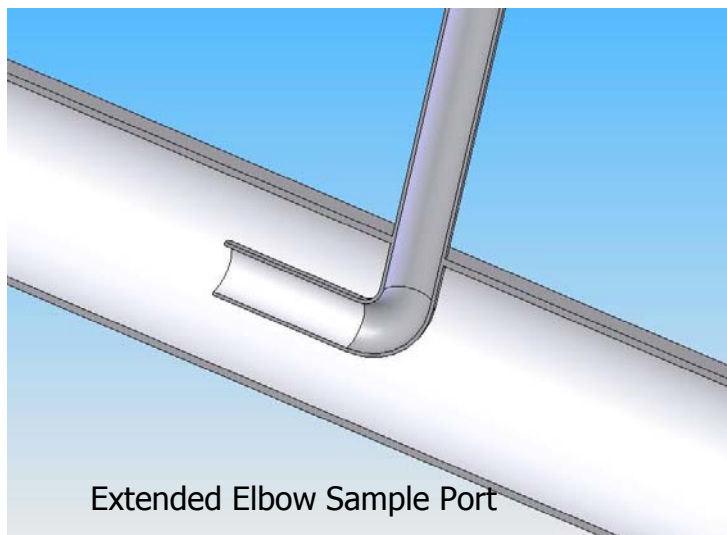
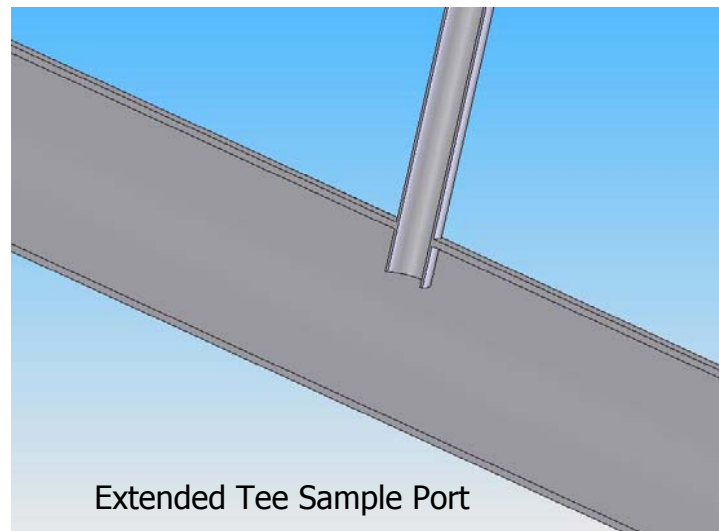
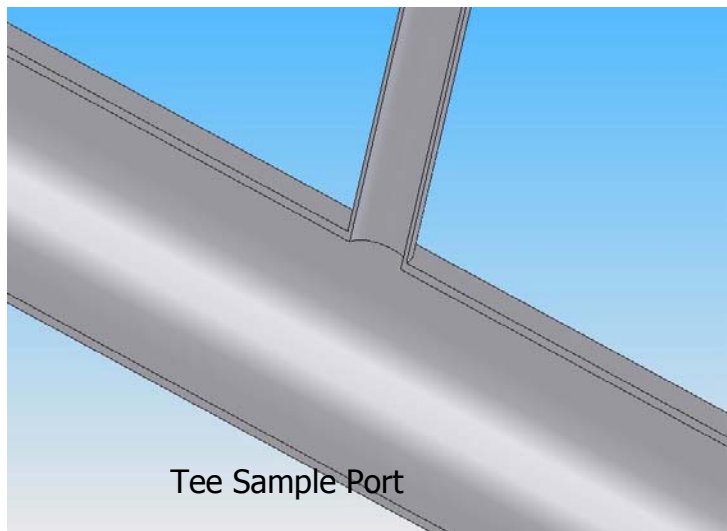


$L_e = 40$ Diameters at 300 m³/hr in a 8" Sch 40 pipe





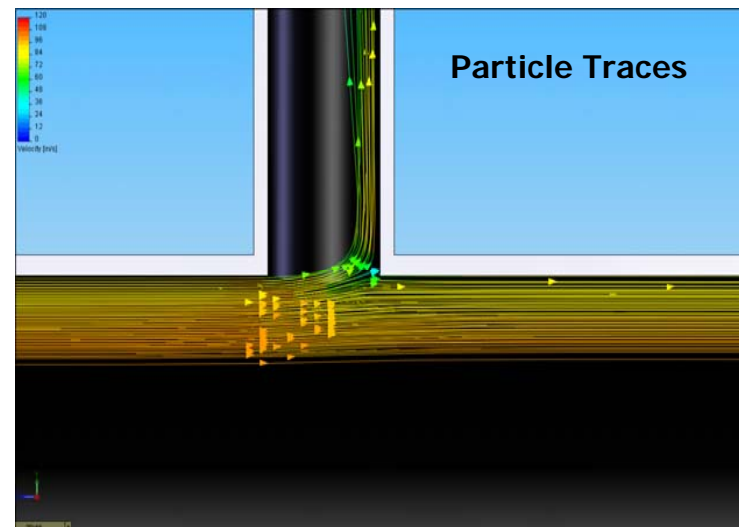
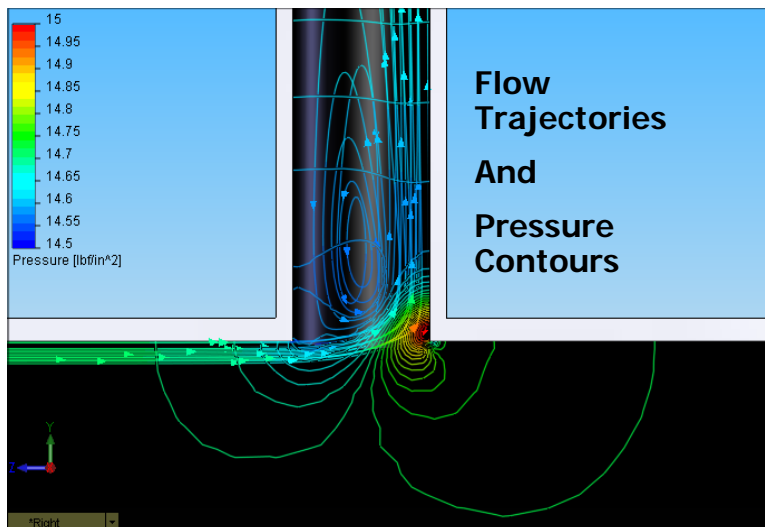
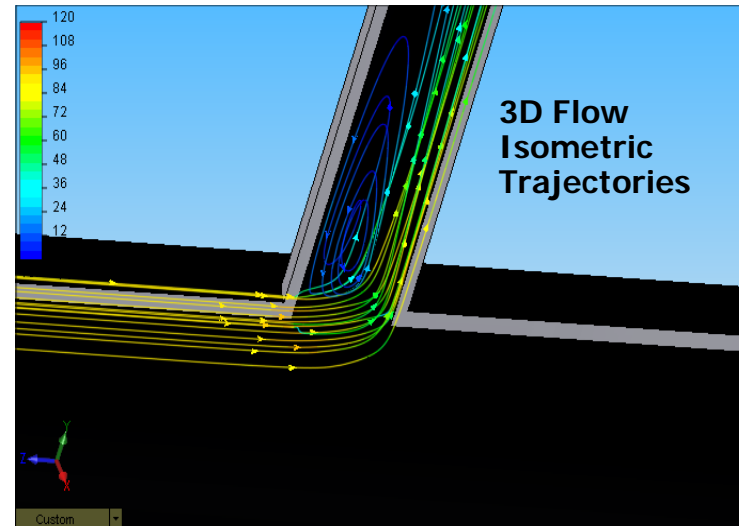
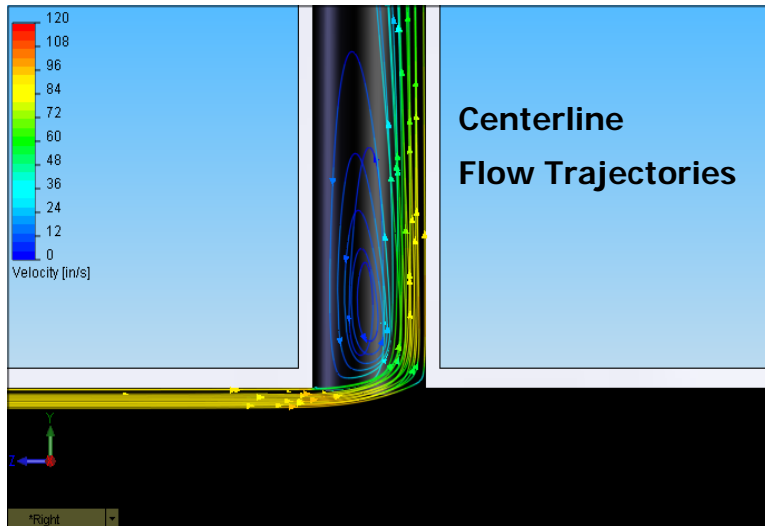
Basic Sample Wand Geometries





Computational Fluid Dynamics of Ballast Water Sampling

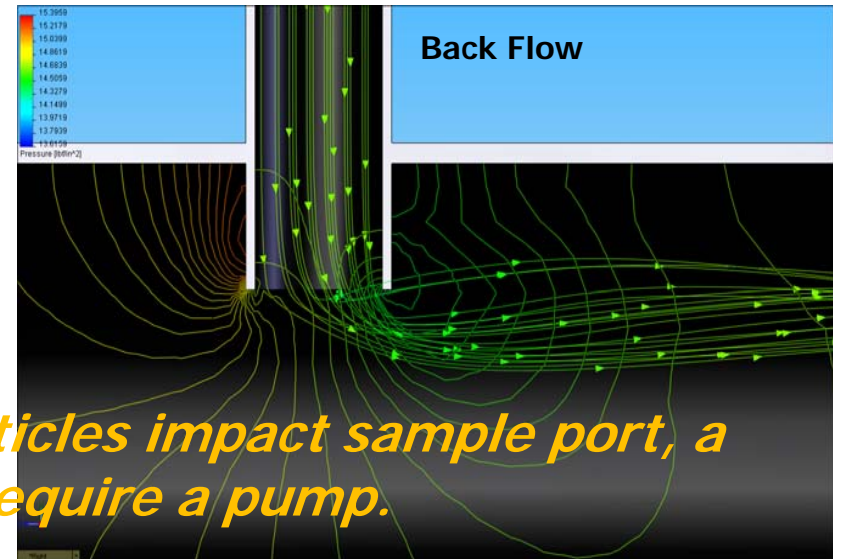
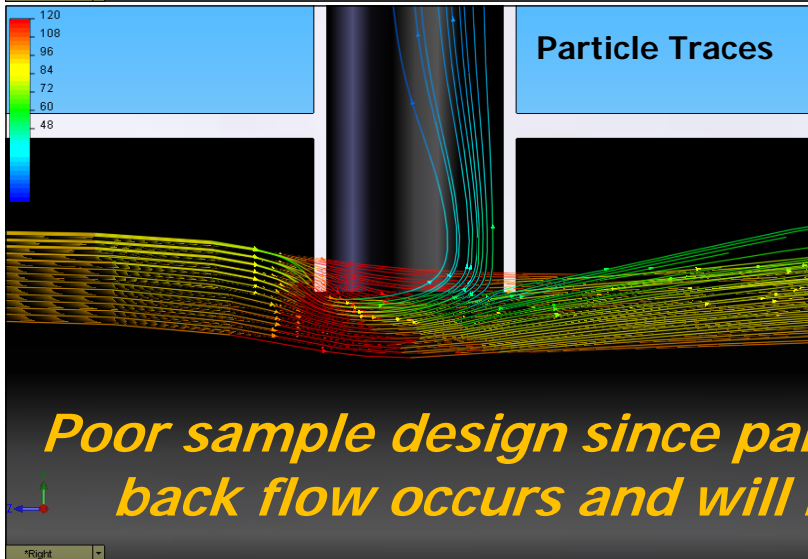
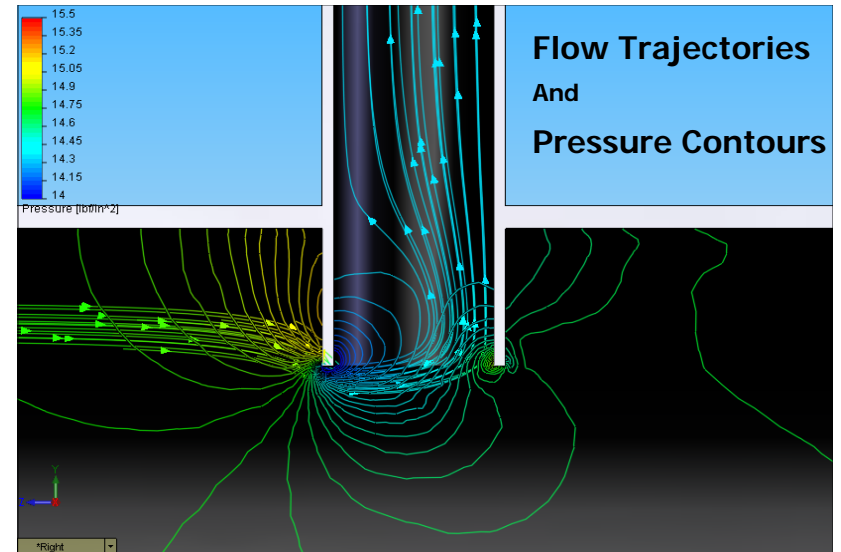
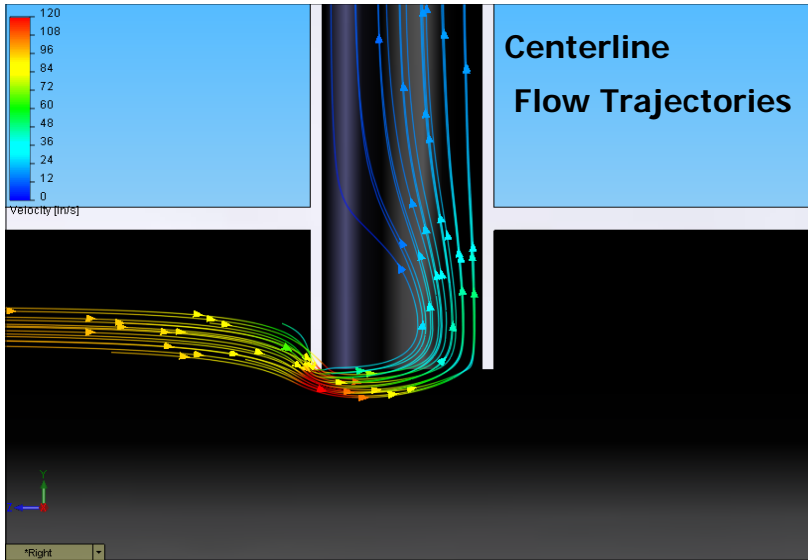
Tee Sample Flow





Computational Fluid Dynamics of Ballast Water Sampling

Extended Tee Sample Flow

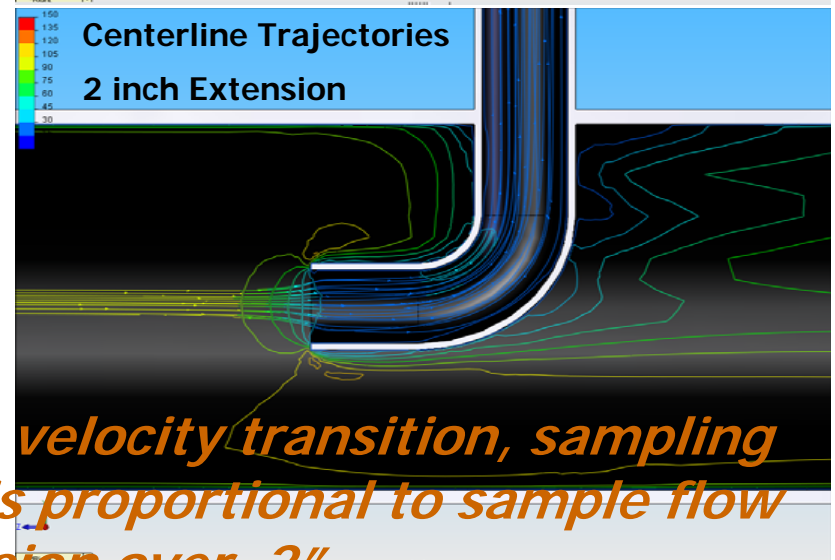
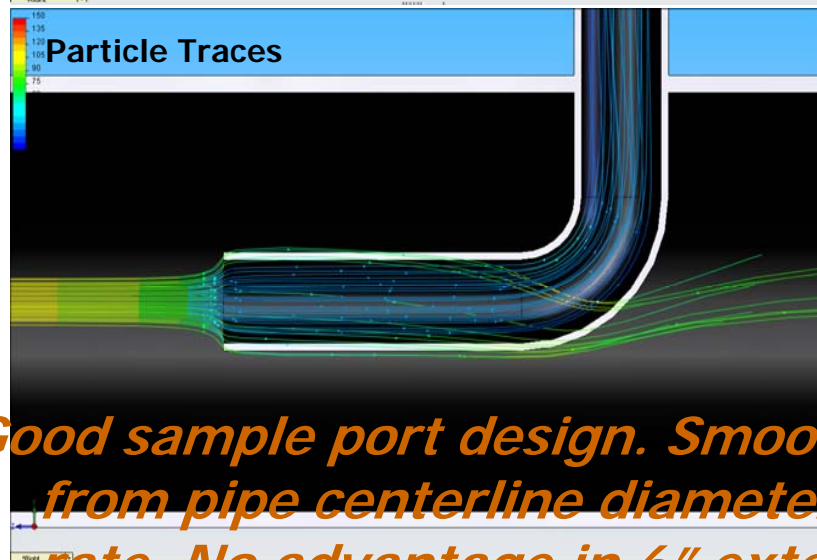
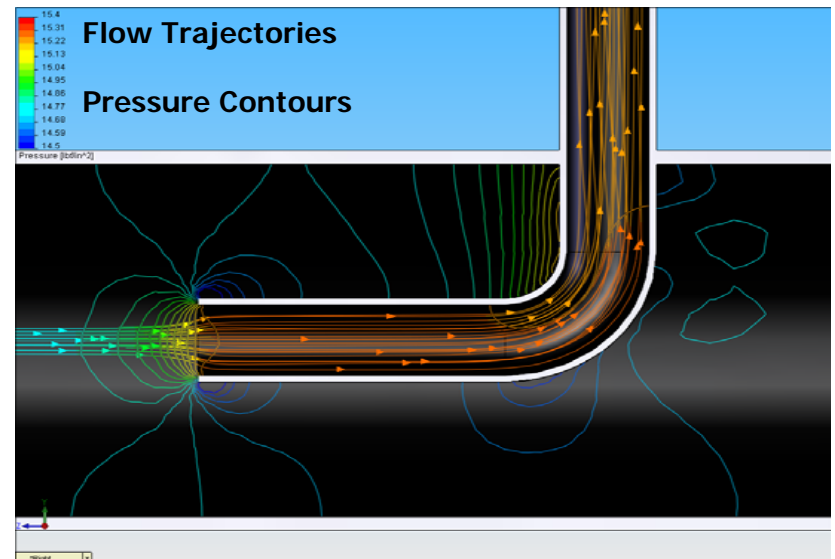
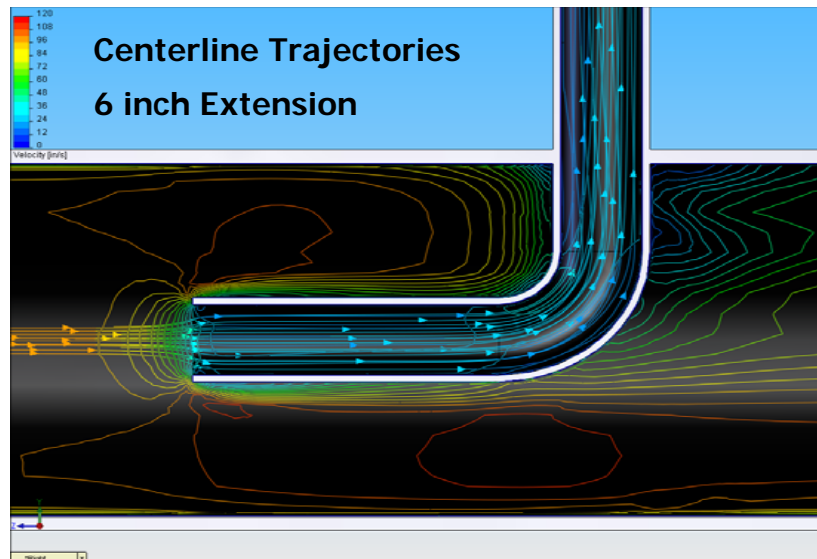


Poor sample design since particles impact sample port, a back flow occurs and will require a pump.



Computational Fluid Dynamics of Ballast Water Sampling

Elbow Sample Flow

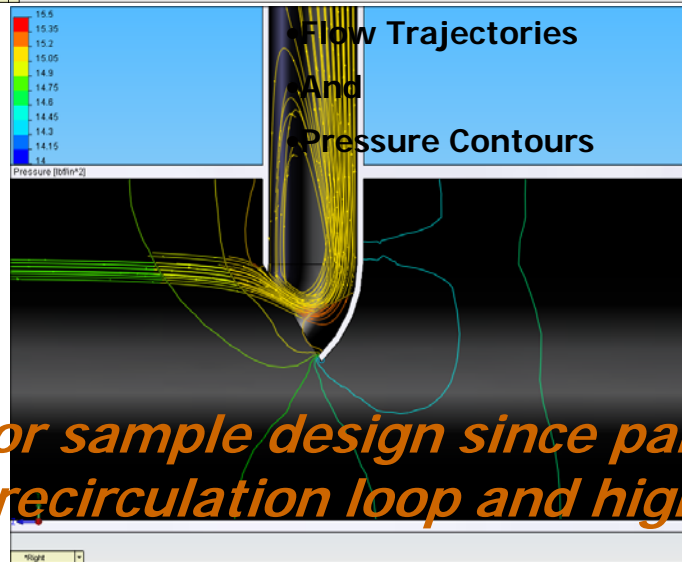
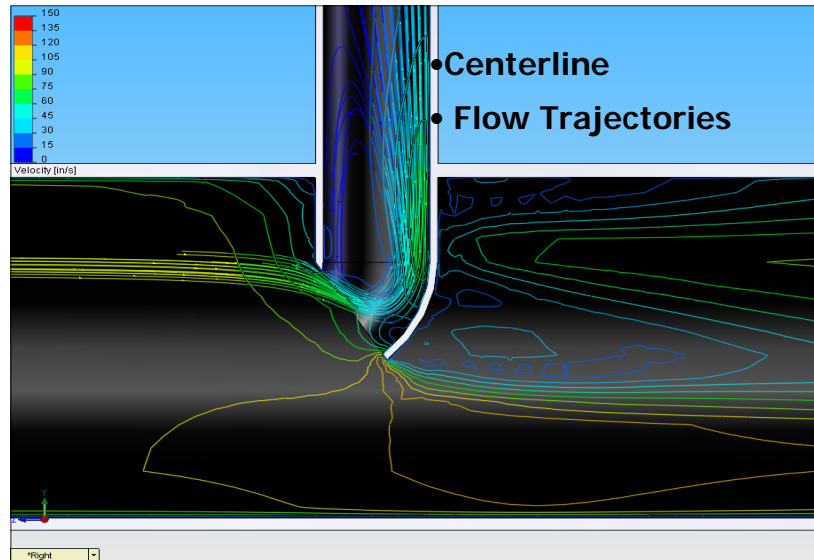


Good sample port design. Smooth velocity transition, sampling from pipe centerline diameter is proportional to sample flow rate. No advantage in 6" extension over 2"

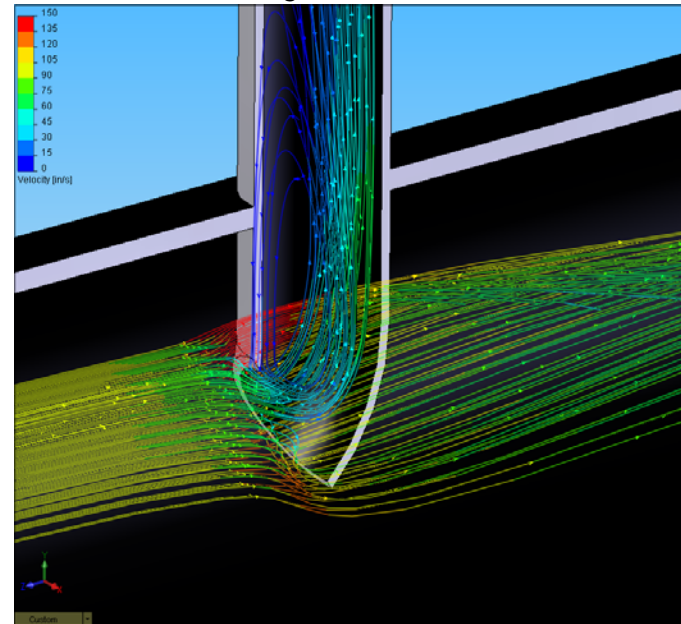


Computational Fluid Dynamics of Ballast Water Sampling

45 Degree Cut-Off Sample Flow



• 3D Flow Trajectories



Poor sample design since particles impact sample port, a recirculation loop and high velocity gradients occur.



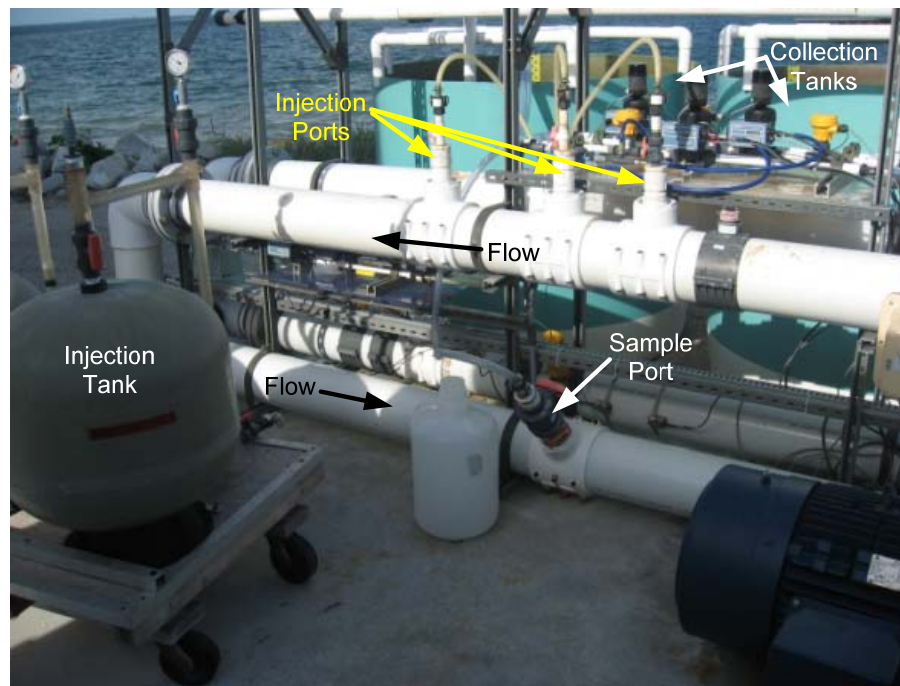
Sample Port Design Findings

- Sample port designs and location have a significant effect on
 - where the sample is actually drawn from within the pipe and flow field.
 - Particle trajectories
 - Particle Velocity and pressure gradients
- Concentric opening and parallel flow samplers were shown to have no eddies or backflow and a reduced likelihood of particle/organism impacts on the sample port.
- Since we assume organism are neutrally buoyant, then organism distribution is homogeneous (well-mixed). However, some organisms will not conform to this assumption (e.g. cysts) and so it is relevant where samples are drawn relative to the flow.
- Well mixed alone is an insufficient description since flow development will also affect sample representativeness and interaction of the organisms with the flow.



NRL KW Ballast Water Test Facility Setup

- Test organisms are injected via hydrostatic pressure down stream of the main ballast pumps.
- Samples then drawn continuously from in line L-shaped sample port, down selected from previous empirical efforts.

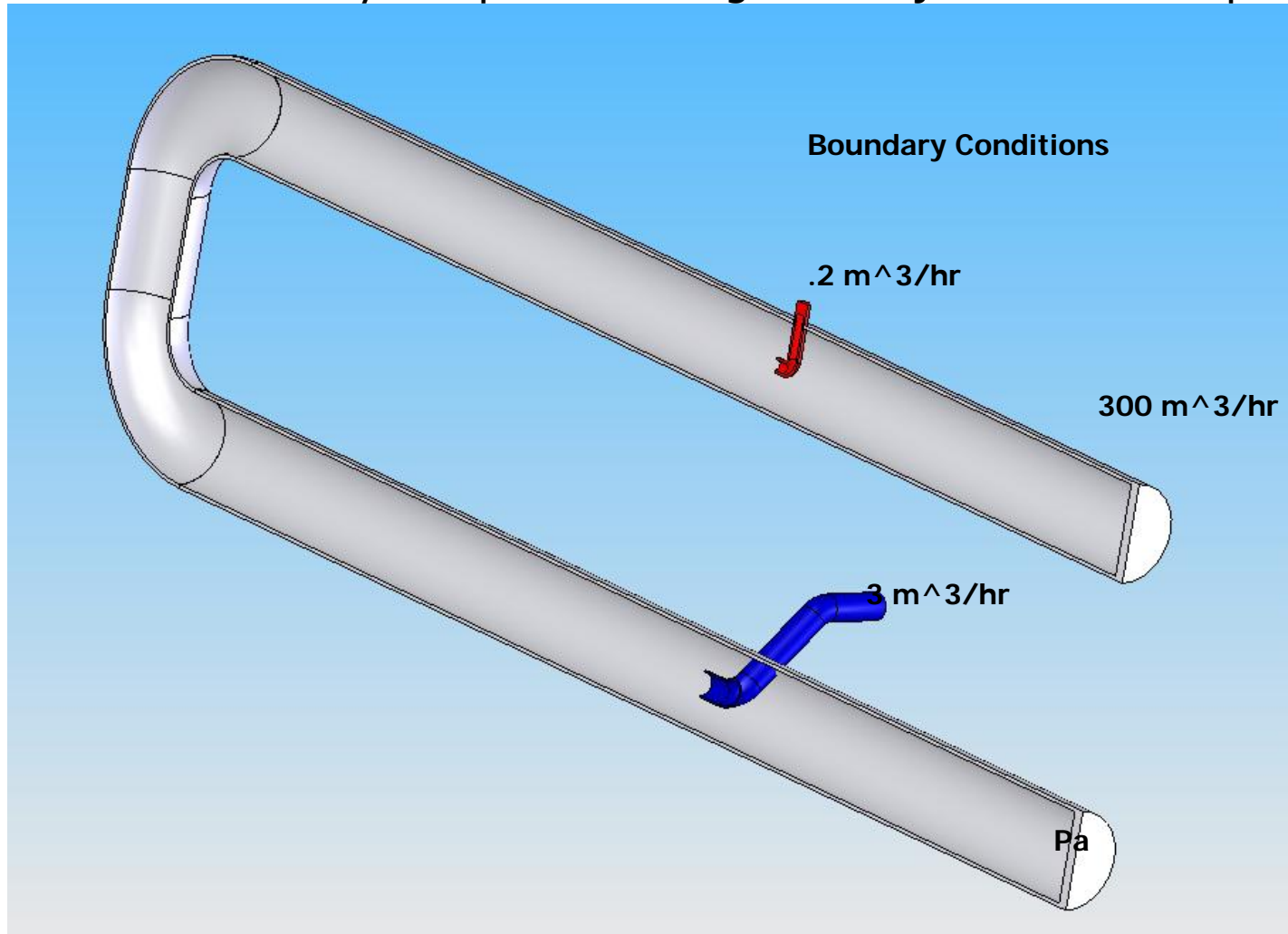




Computational Fluid Dynamics of Ballast Water Sampling

Relative Significance of Sample Port Location and Mixing

NRLKW Test Facility Setup for Test Organism Injection and Sampling

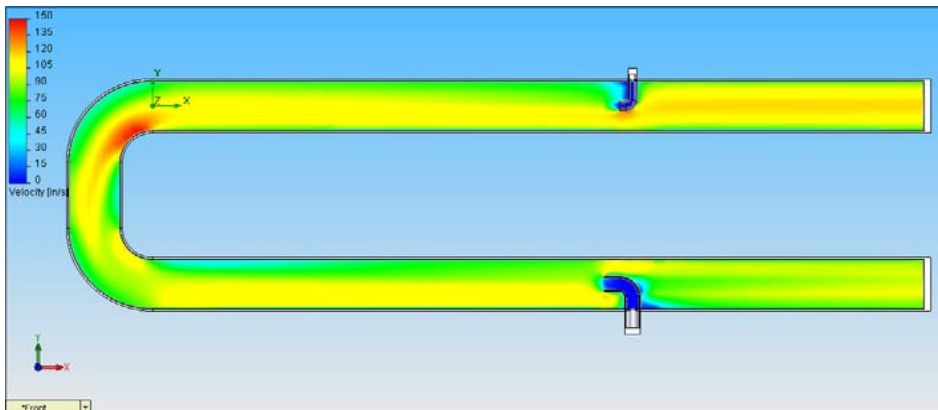




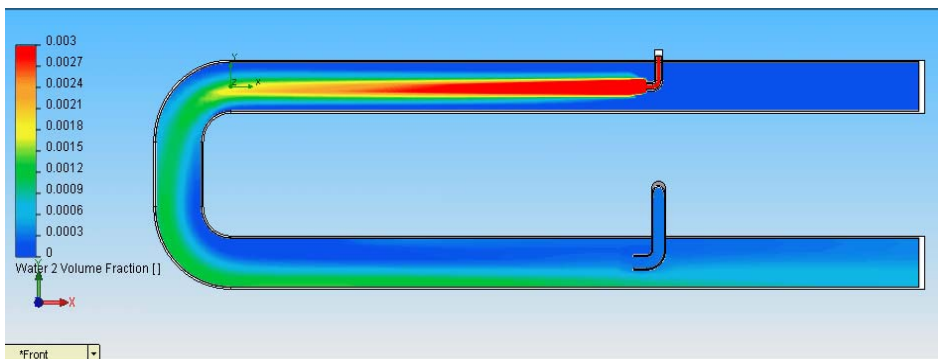
Injected Test Organism Mixing

No Injection

Centerline Velocity Contours



Centerline Volume Fraction Contours

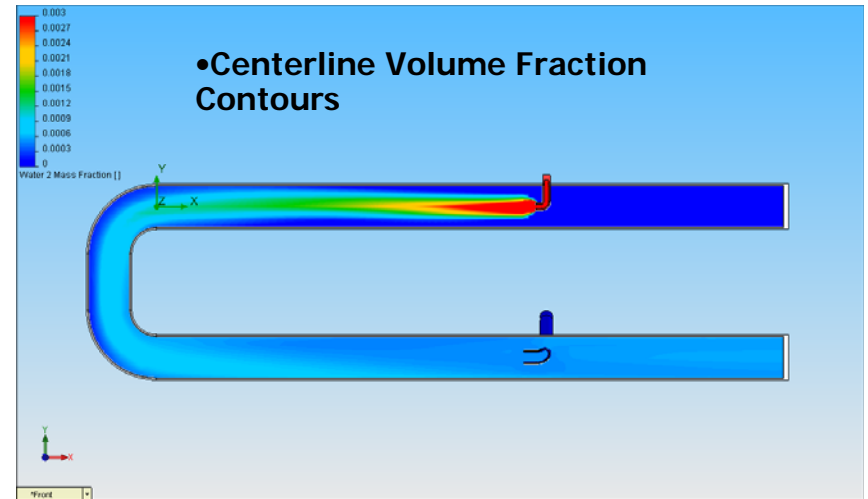
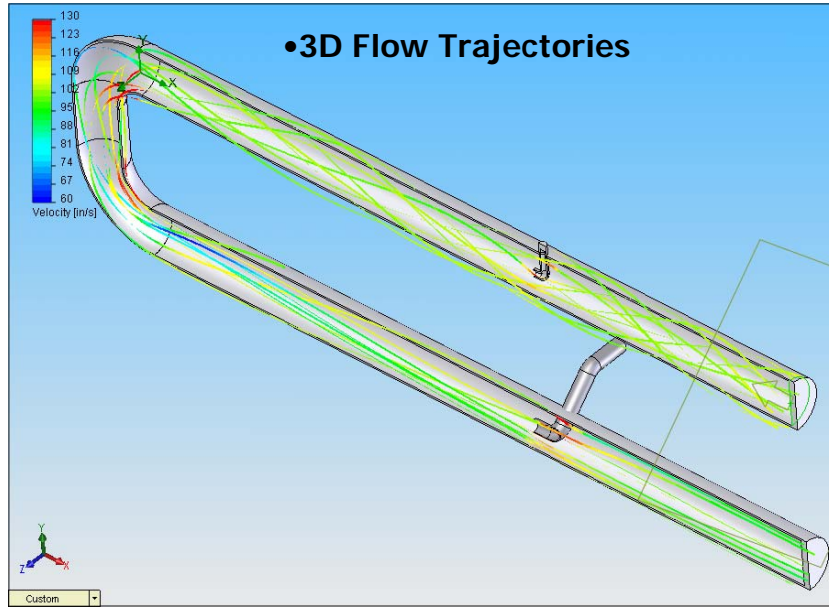


- Without injection, it is apparent that the injection ports and sample ports significantly impact flow/particle distribution downstream.
 - Velocity profile is not uniform at the point of sampling
- With injection this effect is reflected in the volume fraction contours (relative mixing)

Parameter	Value	% Fully Mix
Injected Water Fully Mixed Volume Fraction	0.00056	
Injected Water Fraction at Sample Port	0.00030	54%
Injected Water Fraction at Outlet	0.00056	100.0%



Injected Sample Mixing with Swirl

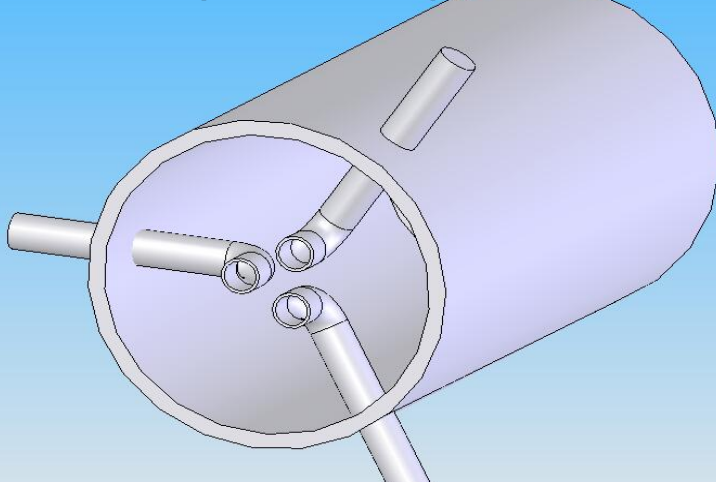


Parameter	Value	% Fully Mixed
Injected Water Uniform Volume Fraction	0.00056	
Injected Water Fraction at Sample Port	0.00051	91%
Injected Water Fraction at Outlet	0.0056	100%

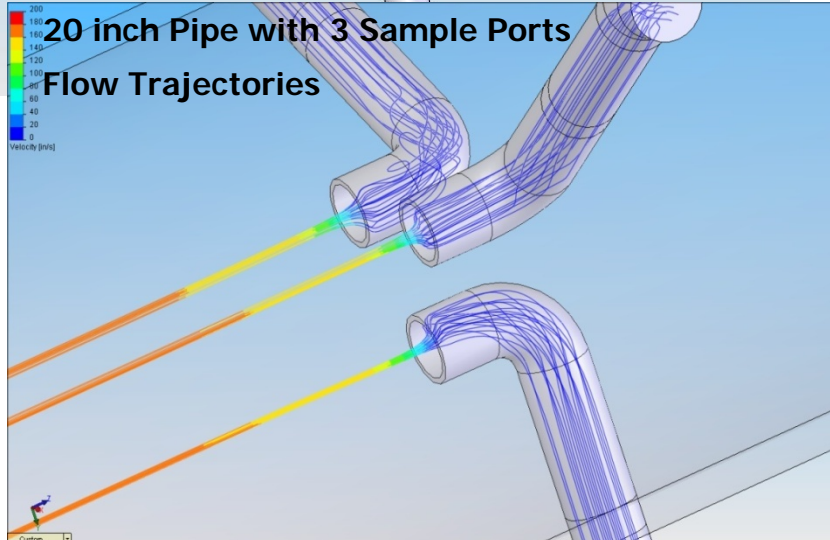


Replicate, Independent Sampling

20 inch Pipe with 3 Sample Ports



20 inch Pipe with 3 Sample Ports
Flow Trajectories

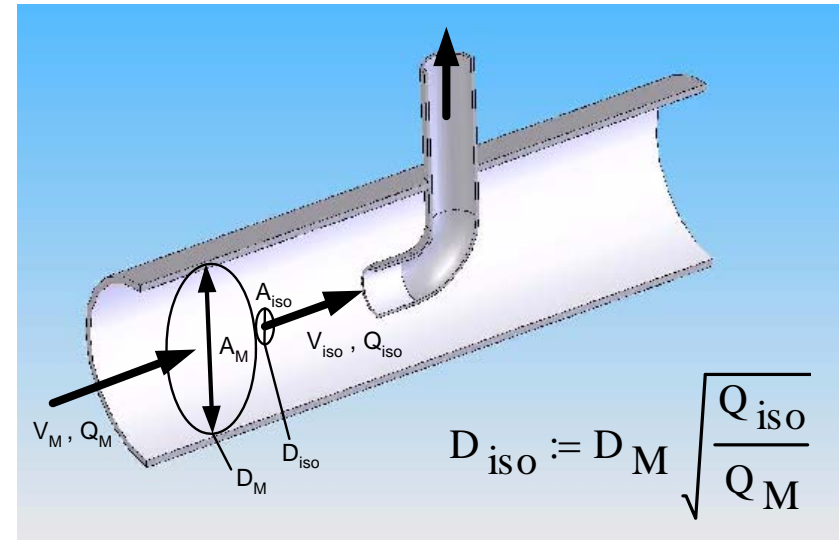


- Flow trajectories into the three sample ports do not interact and are thus independent.
- Flow through the sample wands are identical to those for a single port located at the center.
- For the three ports to truly be at the “same location” in a fluid dynamic sense the sampling must occur in a long straight pipe section to insure that the pipe flow is fully developed.
- May not be realistic for shipboard sampling.



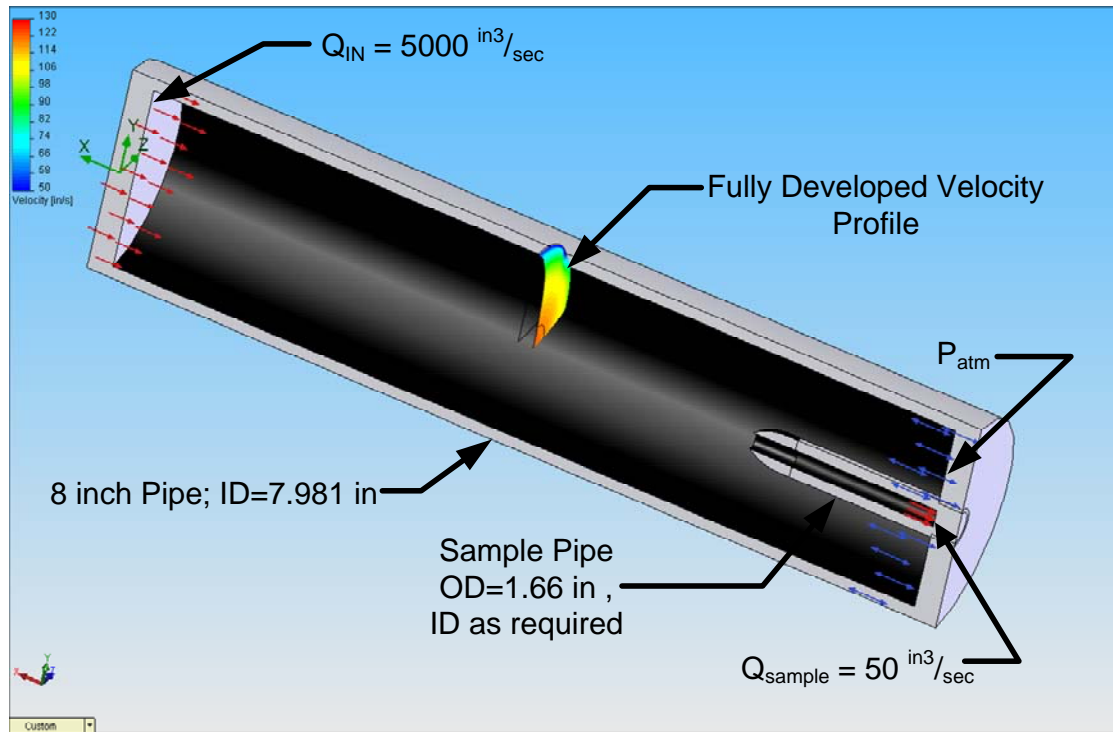
Isokinetic Sampling

- Requires that the velocity profile at the sample port matches the velocity profile in the main stream
- Most often used when testing for constituents with significantly different flow properties that tend to separate due to changes in the flow field
 - ❑ oil/water mixtures where the non-immiscible constituents can separate due to changes in velocity thus biasing the concentrations in the sample.
 - ❑ Separation can also occur when sampling for particles with significantly different densities than the carrier liquid.
- For biological sampling, density and velocity differentials are negligible, the fundamental rules are a useful starting point
- In turbulent flow, isokinetic sampling is nearly impossible due to the high variability and constant fluctuations in instantaneous flow.





Effect of Sample Port Diameter Simulations – Geometry and Boundary Conditions



$$D_{iso} := 7.981 \text{ in} \sqrt{\frac{50 \frac{\text{in}^3}{\text{sec}}}{5000 \frac{\text{in}^3}{\text{sec}}}}$$

$$V_{iso} = 100 \frac{\text{in}}{\text{sec}}$$

$$D_{iso} = 0.798 \text{ in}$$



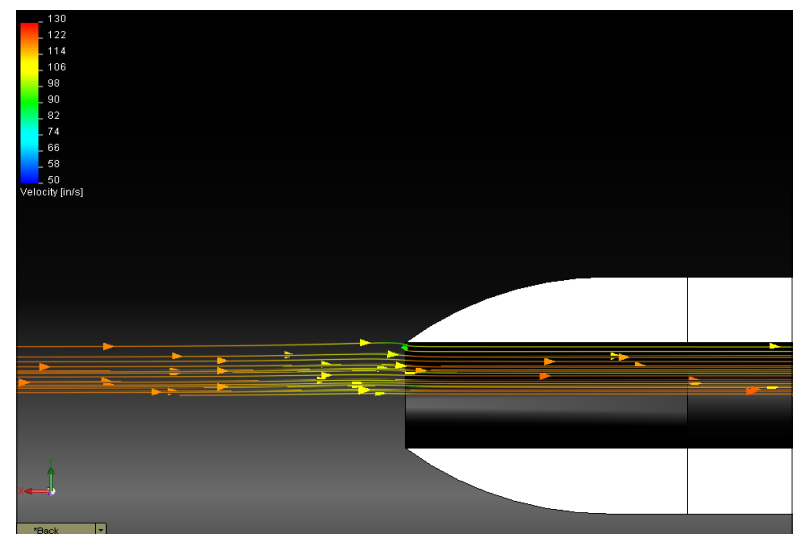
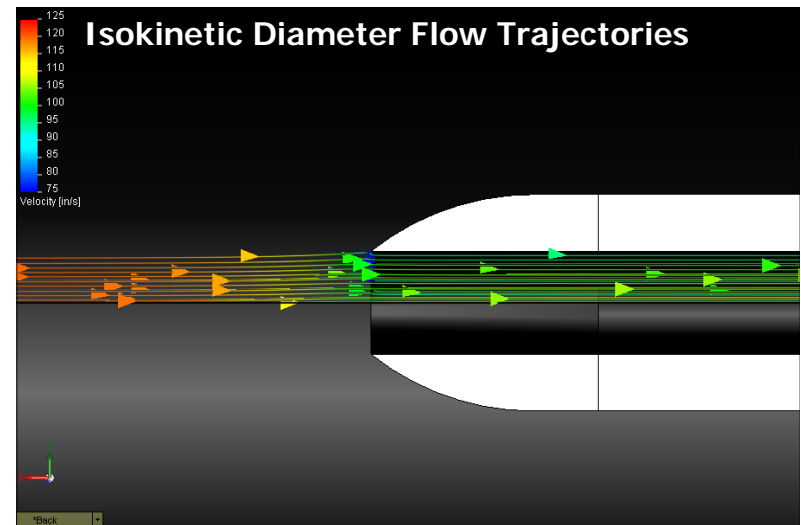
Basic Isokinetic Flow Trajectories

- Note radius edge on sample port, reduces stalling due to pressure increases
- Actual centerline velocity is 119 in/s or 19% higher than average velocity used to calculate the isokinetic diameter
- The theoretical maximum flow velocity is:

$$v_r := \frac{1}{1 + 1.43 \sqrt{f}}$$

- Where f is the friction factor and is a function of the Re and pipe surface roughness

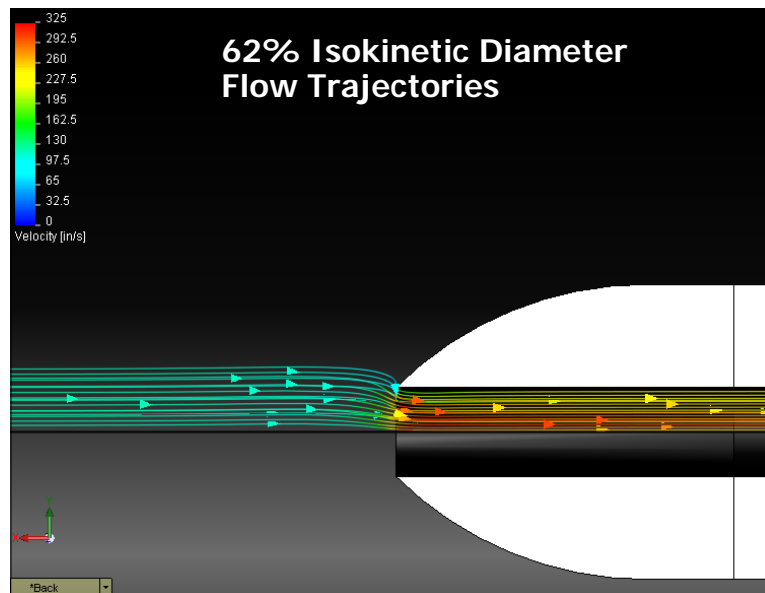
- *Adjustment for maximum velocity not justified as a result of pressure increase and effect on flow field*



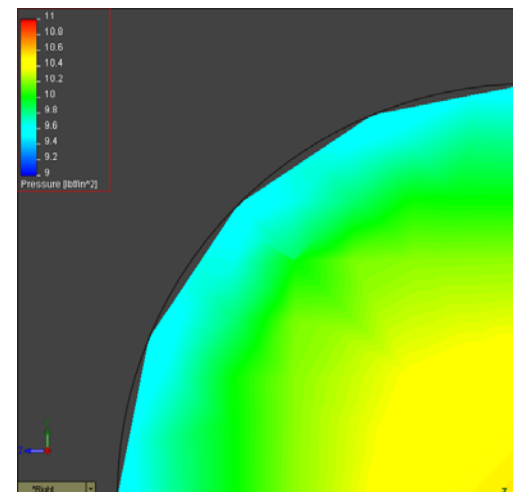


62% Isokinetic Diameter (0.5" Sch 40 Pipe)

- System sampling occurs over the same diameter, but sample velocity is significantly higher with sudden trajectory changes in the outer diameter of the sample.
 - ✦ Increased likelihood of impact with sample wand
 - ✦ Increase likelihood of higher density particle separation
- Overall drop in sample port pressure (to balance increased velocity) which may result in the need for a pump



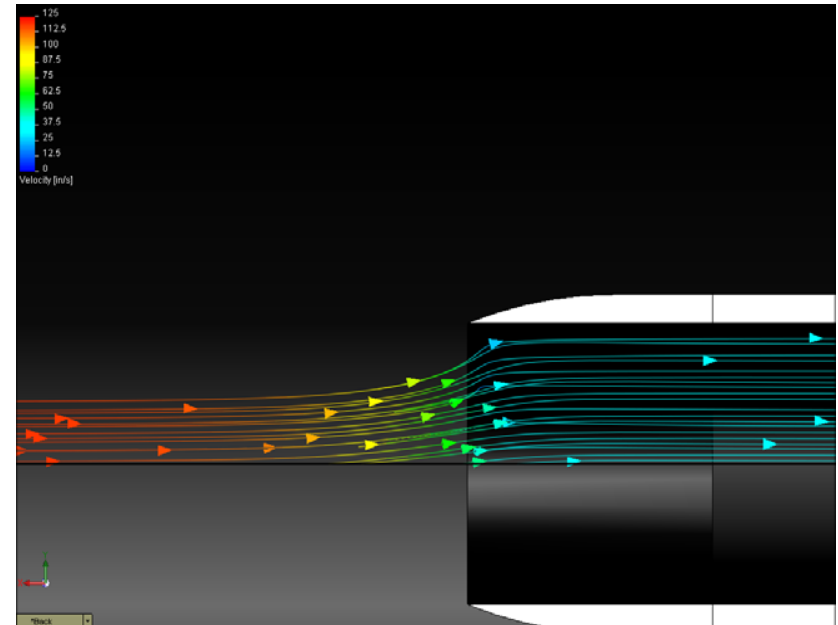
62% Isokinetic Diameter Pressure Contours





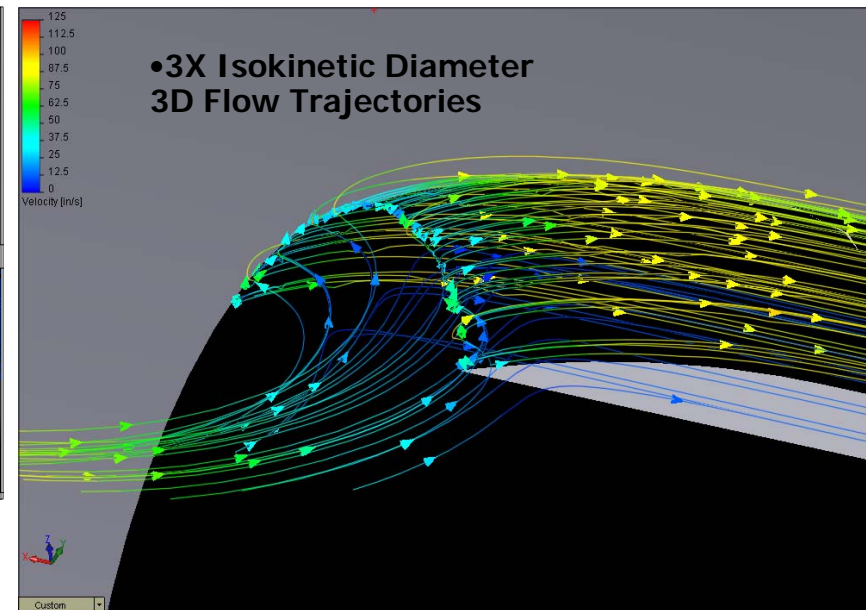
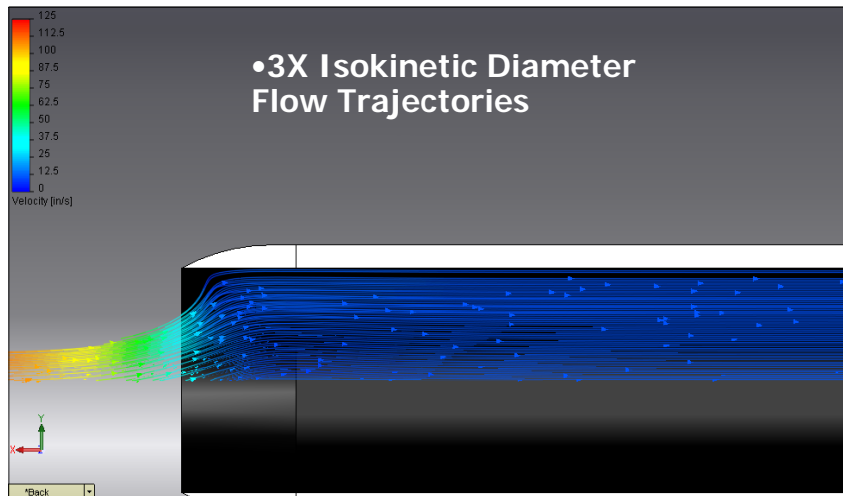
172% Isokinetic Diameter (1.25" Sch 40 Pipe)

- Transition from the main flow to the sampler is essentially the same as the simulation for the elbow simulation.
- The transition occurs in less than one sample port diameter
 - ▣ minimizes any separation of constituents
 - ▣ comes closest of any of the samplers modeled to meeting the intent of isokinetic sampling.
- *Sample Port diameters 1.5-2.0 x the Isokinetic Diameter are recommended for biological sampling of ballast water*
 - ▣ Smooth velocity and trajectory transitions → Reduced organism mortality
 - ▣ Increased pressure in sample port → Negate the need for a sample pump
 - ▣ Moderate resultant changes in velocity are not expected to reduce representativeness





300% Isokinetic Diameter - Effects of Much Larger Sample Diameter

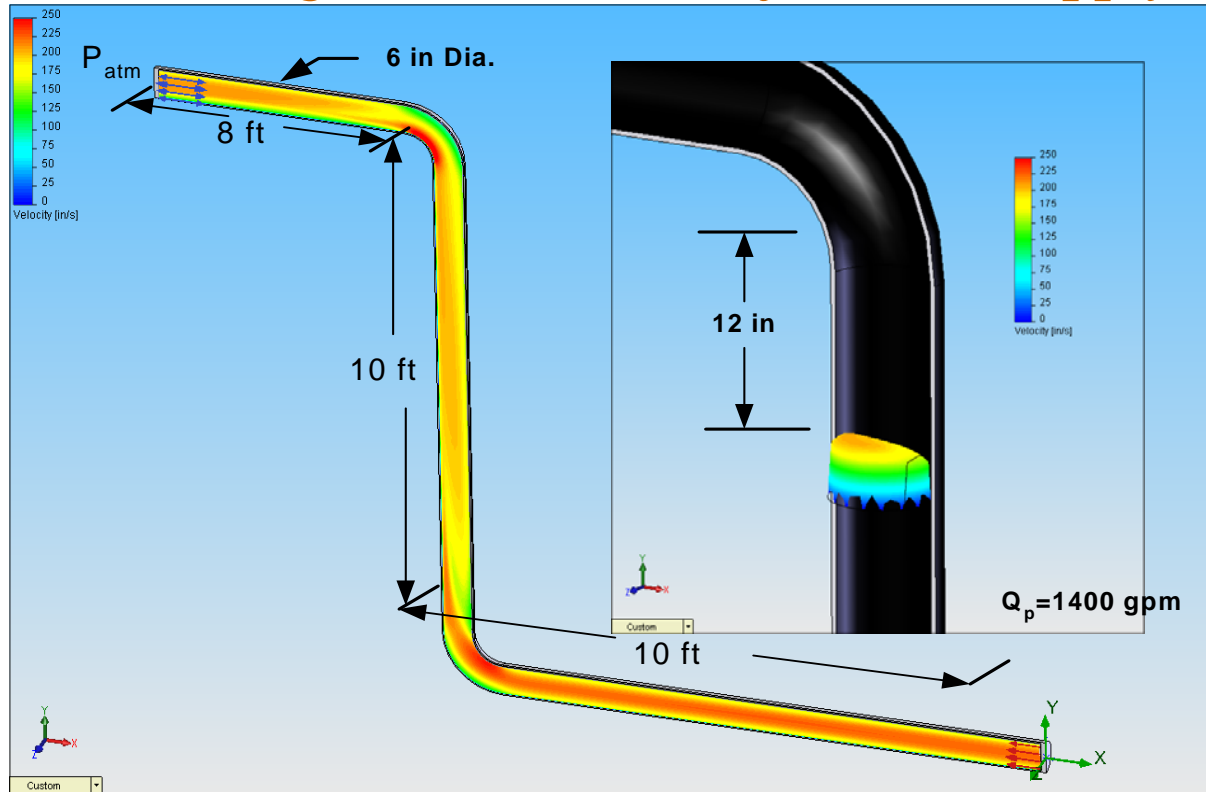


Sample diameters \gg isokinetic diameter result in some back flow and increased likelihood of impacting the sample port wall.



Computational Fluid Dynamics of Ballast Water Sampling

Shipboard Example: NANUQ a 3554 ton, 301 ft Arctic Supply Ship



1400 gpm pump

P&S Bow Ballast
Tanks 300 m³

Discharge Time:

$$T_B := \frac{V_B}{Q_B} \quad T_B = 57 \text{ min}$$

3 m³ Sample Rate:

$$Q_{Sp} := \frac{V_{Sp}}{T_B} \quad Q_{Sp} = 14 \frac{\text{gal}}{\text{min}}$$

Isokinetic Diameter:

$$D_{iso} := D_B \sqrt{\frac{Q_{Sp}}{Q_B}} \quad D_{iso} = 0.6 \text{ in}$$

2 x IsoK Diameter: $2 \cdot D_{iso} = 1.2 \text{ in}$

1 inch Schd 40 Pipe: $D_{INP} := 1.049 \text{ in}$

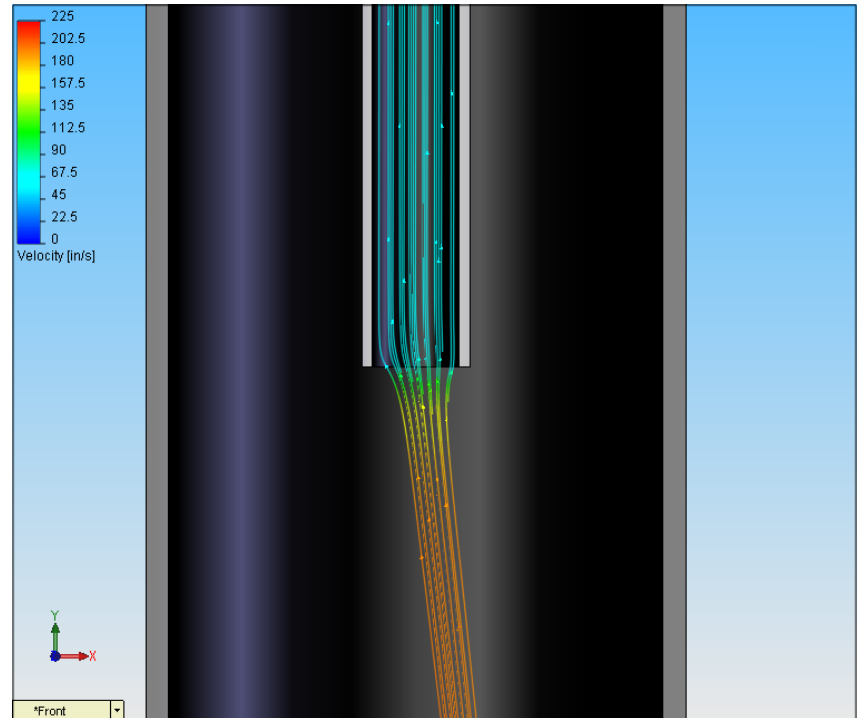
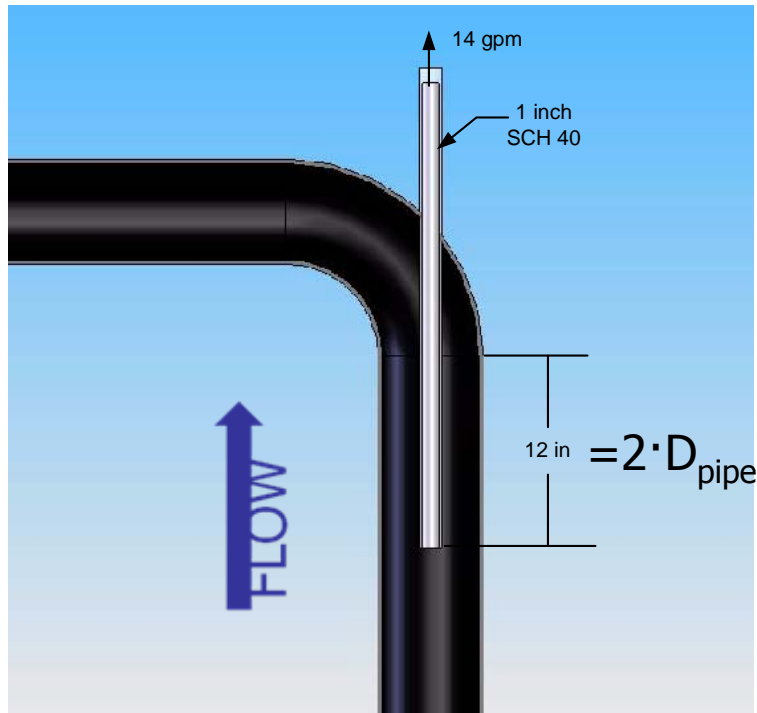
IsoK Ratio:

$$\frac{D_{INP}}{D_{iso}} = 1.748$$

Sample port size should be based on the combination of maximum sample flow rate and minimum ballast flow rate that yields the largest isokinetic diameter.



Shipboard Example: Port Design and Flow Trajectories

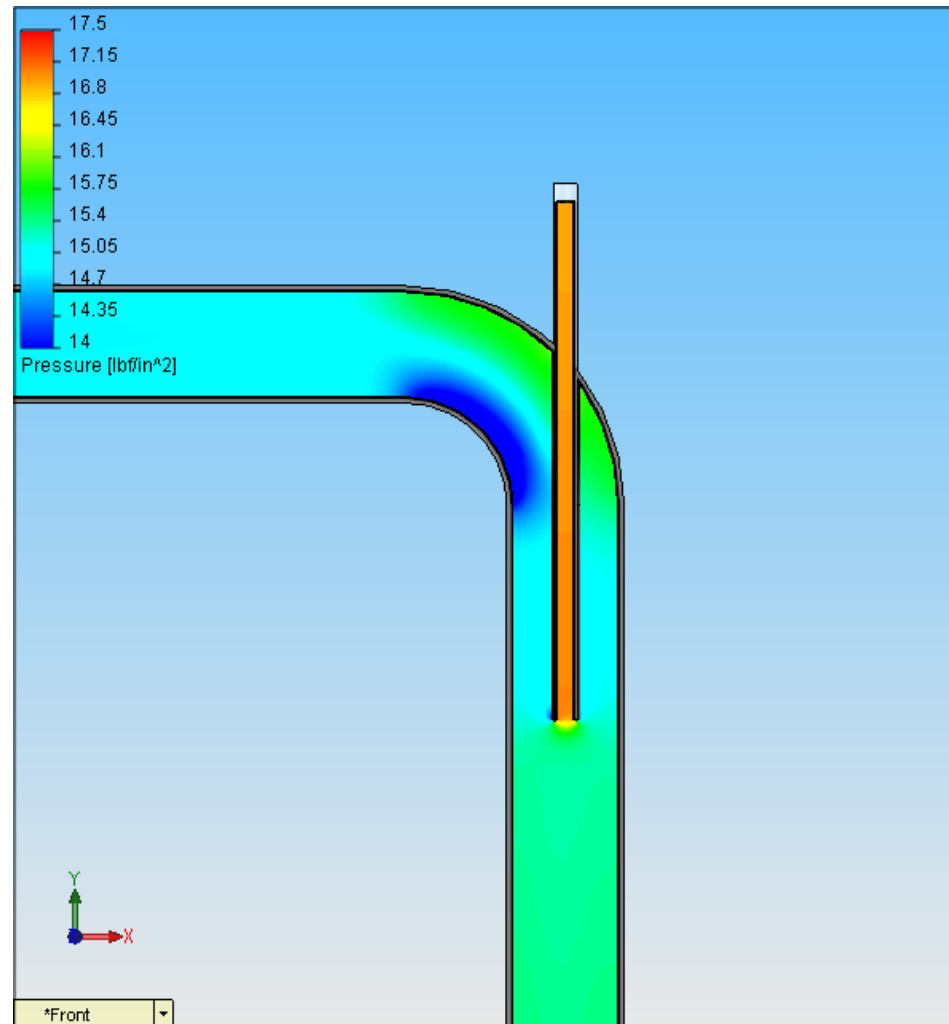


- Vertical orientation negates the effects of gravity.
- The entrance to the wand is located 2 pipe diameters away from the elbow to minimize the effects of the elbow on flow distribution near the port.
- There is a slight off axis skewing of the flow into the port due to the down stream piping and the lack of sufficient flow length in this down stream piping for fully developed flow.



Shipboard Example: Pressure Contours

- The average pressure in the sample port was calculated as $16.9 \text{ psi} > P_a$
 - ✚ no external pump will be required to induce sample flow.
 - ✚ Flow control on the sample line before the collection tank to maintain the desired 14 gpm flow rate.





Sample Port Design and Installation Guidelines

- Sample ports should be located as close to the overboard outlet as possible.
- Ideal sampling is from a long straight vertical pipe section.
- Sample with a straight pipe section on the centerline of the main flow, looking into the flow.
- Sample port diameter should be between 1.5 and 2.0 times the basic isokinetic diameter.
- Sample port size should be based on the combination of maximum sample flow rate and minimum ballast flow rate that yields the largest isokinetic diameter.
- Utilize smooth transition flow controls, like flexible venturies, to control flow rates.
- Minimize the piping and fittings from the sample port to the sample tank or strainer.



Acknowledgements



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